MEASURING SYSTEM FOR TEMPERATURE AND VELOCITY MONITORING IN THERMAL PLASMA SPRAYING PROCESSES.

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ABSTRACT. Conventional optical pyrometry methods do not always yield satisfactory result in case of temperature monitoring in complicated industrial processes [1]. For example, measuring the temperature of heated particles in thermal plasma spraying jets requires recognizing of a measured object by solving a mathematical problem. These algorithms should provide good robustness to ensure real time temperature monitoring. The paper describes system and method for temperature diagnostic utilizing mathematical and physical models of investigated object

KEY WORDS: image analysis, optical pyrometry, thermal spraying, visualisation.

1. INTRODUCTION

A diagnostic system was developed for real-time monitoring of particle-in-flight temperatures, velocities and diameters in thermal spraying processes. The system is based on CCD image sensor providing high sensitivity in near infrared spectral region. An original software package applied for calibration procedure, treatment of the grey image of the powder jet and statistical analysis of the particle parameters is essential parts of the system.

2. DIAGNOSTIC SYSTEM FOR TEMPERATURE MONITORING IN THERMAL SPRAYING

Thermal spraying is a rapidly growing part of materials engineering with its high-performance products applied in a wide range of modern industrial sectors. If strict requirements for the process stability, reproducibility and efficiency can be ensured, the growing range of new spray materials and different substrates will open new areas for thermal spraying applications. The efficiency of optical methods for in-flight particle state monitoring in thermal spraying has been confirmed by different authors [2,3]. One of the most promising ways in optical diagnostics is the application of advanced CCD image sensors [4,5]. However, existing diagnostic equipment based on CCD cameras still remains too expensive for wide industrial dissemination.

3. DIAGNOSTIC SYSTEM DESIGN

The system is based on the advanced CCD image sensor providing high sensitivity in near infrared spectral region. The special design of the CCD camera ensures its operation under strong electromagnetic influence from a plasma gun and ensures reliable data transferring from the camera to the host computer through high-speed 160 Mbps serial HOTLink interface. Due to a built-in internal analog-digital converter the camera provides very low noise level per pixel of $8e^-$ at transfer rate of 6 frames per second for 1.4 Mpix 12-bit grey images. The camera module includes supporting electronics with the incorporated shutter (the range of exposure time is 1 μs to 1 s) and a 12-bit grabber. The information from each brightness channel (pixel) is transmitted to a personal computer in a digital form through a special PCI interface board. The number of effective pixels is 1400×1024; unit cell size (HxV) is 6.45×6.45 μm. An achromatic telecentric lens provides an opportunity to monitor the powder jet within the chosen area (28x20) mm for 150 mm from a plasma jet). Pixel-by-pixel digitalization of CCD matrix signals as a result gives all the pixels intensities that are used for temperature, velocity and diameter of a particle determination.

Block diagram of the diagnostic system installed as a detached device for plasma spraying monitoring is presented in Fig. 1. The dimension and weight of the diagnostic system allow an easy installation as a detached device or by direct camera mounting on the plasma torch. The basic diagnostic system is a monochromatic one. For measuring of brightness temperature were used two broadband filters at $\lambda_{P1} = 0.76$ μm or $\lambda_{P2} = 0.8$ μm with bandwidth 100 nm and 15 nm correspondently. First used for temperature

monitoring of powders with low radiant émittance and low melting temperature. Working wavelength easily can be changed in the range 0.6–1.0 μm by replacing the filters. The main characteristics of the diagnostic system are presented in table 1.
A special test field (a set of size-calibrated objects) and the blackbody source (temperature range of 1000 to 2900 °C, accuracy ±5 °C) were used both for the static and dynamic calibration of the developed diagnostic system. A rotating disk with small circular holes (∅ 40 to 120 μm) was used to imitate particles passing through a focal plane of the diagnostic system. The system determines particle size, so it is possible to correct for the size of source effect during measurement of its temperature. Calibration results are recorded as a file and are used for brightness temperature calculation in a measurement cycle. In addition, correct deconvolution of the particle diameter was tested in a plasma spraying process by use of mono-disperse (ZrO_2+8%Y_2O_3) powder of size 64±5 μm. The performance of the diagnostic system is shown in Table 1.

3. METHOD OF MEASUREMENT OF PARTICLE PARAMETERS

Digital data flow is controlled by specially developed software allowing the control of the CCD camera supporting electronics, automatic camera calibration, process monitoring, data recording, grey image analysis, data statistical treatment, data presentation and real-time monitoring of powder jet mean values. Pixel-by-pixel 12-bit digitization of the CCD matrix signals is applied in the diagnostic system. As a result, each frame is represented by all the pixel intensities that are recorded in a data file.
A grey scale video image is based on this data file. Flying particles are presented on this video image as light tracks with different width, length and intensity (Fig. 3).The length of the track is proportional to the exposure time. The width of the track is proportional to the particle diameter. The particle diameter can vary over a wide range from 10 to 150 μm thus making an accurate definition of the particle diameter critical for image analysis.

4. THE MATHEMATICAL ALGORITHM OF PARTICLE PARAMETERS DETERMINATION

The original mathematical algorithms were designed and applied for grey image treatment in combination with the fine procedure of calibration of optical distortion and non-uniformity of the CCD matrix allows reaching of sub-pixel resolution in the particle diameter measurement. A special software package was developed for calibration procedure, treatment of powder jet grey image and statistical analysis of particle parameters was designed.
A special algorithm so-called sub-pixel resolution [6] applied to grey image data allows reaching 0.1 pixel (or ~1 μm) resolution in the particle diameter measurement. Developed program module allows automatic real-time recognition of “good” tracks and definition of their geometry with sub-pixel resolution. A “good” track should meet the following requirements:
1. The particle is situated in a thin focal plane;
2. The track does not cross the border of the image;
3. The track does not cross other tracks.

The treatment procedure includes three main stages:
1. Initial image filtration for high frequency rejection;

2. Track allocation: determination of the pixels belonging to the particle track and final formation of the track geometry;
3. Measurement of the particle parameters: temperature, velocity and size.

4.1. INITIAL IMAGE FILTRATION FOR HIGH FREQUENCY REJECTION

Smoothing of the initial image is used to solve this problem. This procedure suppresses high frequency components of the horizontal intensity profile, while retaining low frequency informative components at the same time (Fig. 4). The procedure is based on pixel-by-pixel transformation of initial image intensity by using developed likelihood criterion (2)

$$I_{Sm}(x,y)=\left\{\begin{array}{l}\left(1-\dfrac{\sigma^2\min}{\sigma^2 signal}\right)*\left(I(x,y)-m\right)+m,\ \text{if } \sigma^2_{signal}>\sigma^2_{\min}\\ m,\ \text{if } \sigma^2_{signal}<\sigma^2_{\min}\end{array}\right\}, (2)$$

where $I_{Sm}(x,y)$ и $I(x,y)$ intensity values in pixel (x,y) for smoothed and initial images respectively; m, σ^2_{signal} – mean and variance in neighborhood 10x3 of pixel (x,y), $\sigma^2_{\min}$ - noise variance (accepted as constant).

4.2. ALLOCATION OF PARTICLE TRACKS

At this stage, the smoothed image is treated by non-linear rank filtration related to the track-borders allocation procedure [6, 7]. The surroundings S of each image element are defined, and pixels included in this area are arranged in terms of ascending brightness. For the given type of objects the accepted size of the surrounding is 21 pixels.

In case of classical rank filter of order R the intensity value of central pixel (x,y) in area S corresponds to intensity of pixel with rank R $I_R(x,y)=I((x,y)_R)$. In other words the output value domain of rank filter is intensity values.

For allocation of particle tracks the classical rank filter was modified in such a way that the intensity of each pixel of the smoothed image has a certain value relative to its rank in area S $I_R(x,y)=R(I_{Sm}(x,y))$. As a result the output value domain is rank values that provide suppression of points with low intensity and retaining points with high intensity. A set of pixels belonging to the particle track is formed by special line-following algorithm. The inclusion criterion is that each point with a rank value higher than half the rank of its surroundings is accepted as a particle track point. (Fig. 5).

To determine the track geometry with sub-pixel resolution the least-squares method (3) is applied by using the set of previously detected track points.

$$x = k * y + b,$$

$$k = \frac{n * \sum_{1}^{n} x_i * y_i - \sum_{1}^{n} x_i * \sum_{1}^{n} y_i}{d}$$

$$b = \frac{\sum_{1}^{n} y_i^2 * \sum_{1}^{n} x_i - \sum_{1}^{n} y_i * \sum_{1}^{n} x_i * y_i}{d} \quad (3),$$

$$d = n * \sum_{1}^{n} y_i^2 - (\sum_{1}^{n} y_i)^2$$

where (x_i, y_i) - point of particle track detected by line-following algorithm, n – number of particle track points, line x=k*y+b sets the sub-pixel particle track.

4.3. VELOCITY AND DIAMETER DETERMINATION

The width of the track is defined by the following method. Several track surroundings are considered. Three different statistical hypotheses of track shape (intensity along the track length) are tested:

1. Flat shape - no signal;
2. Sharp edges – ‘roof’ shape;
3. Diffuse edges – ‘π’ shape.

Particle tracks with ‘roof’ shape are accepted as ‘good’ tracks. The decision about track shape is made by evaluating likelihood criterions (4, 5)

$$SNR_{\mathrm{H}_1/\mathrm{H}_2} = \sqrt{\frac{\sigma^2_{H_1}}{\sigma^2_{H_2}}} \quad (4),$$

$$SNR_{\mathrm{H}_1/\mathrm{H}_3} = \sqrt{\frac{\sigma^2_{H_1}}{\sigma^2_{H_3}}} \quad (5),$$

where $\sigma^2_{H_1}$ - signal (track intensity) variance relative to model of flat shape; $\sigma^2_{H_2}$ - variance relative to model of ‘roof’ shape; σ^2_{H3} - variance relative to model of ‘Π’ shape.

Environment *S* of the particle track where likelihood value (4) is maximal and exceeds experimental threshold is accepted as integer-valued width of the track.

The convolution of the horizontal profile in the defined integer-valued environment *S* with Gaussian mask *G* {1 8 28 56 70 56 28 8 1} is realized in each cross section of the track. The intersection of the initial signal with the convolution signal (Fig. 6) allows determination of the track width with sub-pixel resolution [6, 7]. The width along the track is determined by the least-squares method (3) allowing maximum accuracy.

4.4. EVALUATION OF TRACK EDGES SHARPNESS BY MORPHOLOGICAL FILTERING

Along with method of statistical hypotheses testing, the sharpness of particle track edges is evaluated by performing morphological filtering. Mathematical morphology [8, 9] is a set of theoretic methods for shape-based detection and analysis of objects on digital images. Operations of mathematical morphology are defined as operations between examined signals and a set of simple shapes, called structuring elements. Shape and size of structuring elements determine which points in the image object are affected by the operation. In other words structuring elements must adapt to the shape of examined object. Usually, certain knowledge about shape of target objects exists, so structure elements are selected in advance. For given objects the structuring element was defined as disk with radius R=3 pixels.

To evaluate the sharpness of particle track edges the operation of morphological opening is applied to intensity profiles in each cross section of the track. Opening consists of two consecutive operations – first erosion (has effect on image background), then dilation (has effect on image foreground). Erosion and dilation calculates minimum and maximum of differences between values of signal (intensity profile) and structuring element points. Separately erosion and dilation suppress the signal details smaller than the selected structuring element but cause a global geometric distortion of unsuppressed features. Consecutive implementation of these operations helps to avoid such distortion [8, 9].

Since the signal details smaller than the structuring element are suppressed by morphological opening, the track edges sharpness can be evaluated by calculating differences between initial signal and the result of morphological opening (Fig. 7). Particle tracks with difference value DeltaH lower than the experimental threshold are defined as tracks with diffuse edges and not considered in further processing.

When “good” tracks and their parameters are determined (Fig. 2), the particle diameter, speed and brightness temperature are calculated for each particle. Accumulated data are presented in the form of statistical histograms.

In order to increase reliability of the developed methods for particle tracks allocation, all experimental thresholds in algorithms are determined by self-organized neural network. This network is based on extensive database of digital images of particle flow and provides optimal solution in choosing values for algorithm parameters.

5. TEMPERATURE DETERMINATION

In a majority of industrial applications, only the brightness temperature is required for process stability and quality control. It gives an opportunity to simplify the design of the diagnostic system (monochromatic version) and, as a result, to ensure a relatively low price affordable for small spraying job shops. Nevertheless, in some cases (development of new technological methods, process optimization, new powder blends processing, etc.) information on the particle true temperature is required. For correction of the brightness temperature, the system is supported by a database on spectral emissivity of different industrial powder materials.

6. TESTING THE SYSTEM IN PLASMA SPRAYING

The developed diagnostic system has been tested for different types of industrial processes and a wide range of powder materials. In the present article only one example of the CCD camera application in plasma spraying is considered. A TAFA system was used in this trial. Spraying of Cr_2O_3 powder (size 22 to 45 μm) was studied. The CCD camera was sighted on the center of the plasma jet at a typical spraying distance from the plasma gun nozzle.

Histograms for nominal spraying conditions are presented in Fig. 8. The jet mean temperature is 2114 °C for Cr_2O_3 powder. The spread of particle temperatures is in the range 1900 to 2450 ^{o}C. The instrument readings (10 to 45 μm) are in a good agreement with the specification of the supplier of the Cr_2O_3 powder (22 to 45 μm), indicating that the measuring system accurately measures the powder size distribution. The presence of small particles (<22 μm) may be explained by partial evaporation of particles in the plasma jet.

7. CONCLUSION

The CCD based diagnostic system was tested [1] for different types of industrial processes: Plasma spraying, HVOF, Flame Spraying, and Wire Spraying. Wide range of powder materials and well-known spraying equipment (Plasma Techik, Sulzer Metco, TAFA, CDS, etc) were used in experiments. It was found that the system is sensitive enough to detect the influence of different process parameters (arc current, powder flow rate, etc.) on the particle velocities and temperatures. The system can be also used as a fast CCD camera for visualization of the particle collision with the substrate, coating growth, cracks generation and full jet visualization.

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Table 1. Specification of the diagnostic system.

Temperature range, °C	1000 - 3500
Particle size detection limit, μm	10
Maximum particle velocity, m/s	1200
Working wavelengths λ_P, μm	0.76 or 0.80
Instrumental error, %	± 1
Distance from a jet L, mm	150 - 200
Minimum exposure time, μs	1
Weight, kg	1.7
Power consumption, W	7
Optical head dimensions, mm	200×170×80

Fig. 1. Block diagram of CCD camera module with supporting electronics

Fig. 2. Block diagram of the diagnostic system installed as a detached device for plasma spraying monitoring.

FIG. 3. Flying particles are presented on a digital video image as light tracks. Marked tracks are “good” tracks determined in real time automatically by the created software.

FIG. 4. Intensity profile of initial (a) and smoothed (b) image.

a). Intensity profile of initial image

b). Intensity profile of smoothed image

FIG. 5. Allocating points of particle track

FIG. 6. Determination of the track width with sub-pixel resolution

FIG. 7. Evaluation of track edges sharpness by morphological filtering. Evaluation criterion is DeltaH value

FIG. 8. Histograms of powder diameter and temperature for nominal spraying conditions.

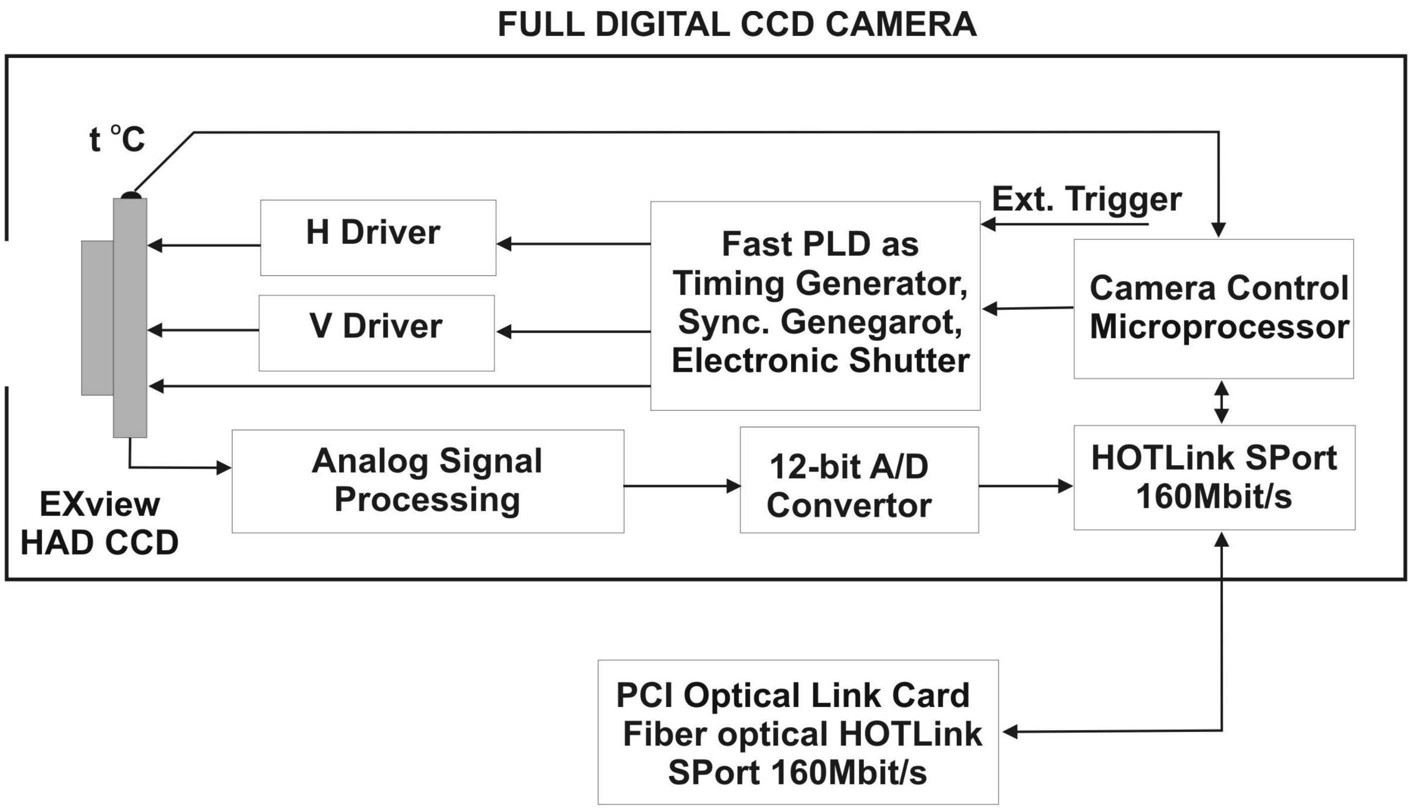

FULL DIGITAL CCD CAMERA
t °C
H Driver
V Driver
Fast PLD as
Timing Generator,
Sync. Genegarot,
Electronic Shutter
Ext. Trigger
Camera Control
Microprocessor
Analog Signal
Processing
12-bit A/D
Convertor
HOTLink SPort
160Mbit/s
EXview
HAD CCD
PCI Optical Link Card
Fiber optical HOTLink
SPort 160Mbit/s

FIG. 1.

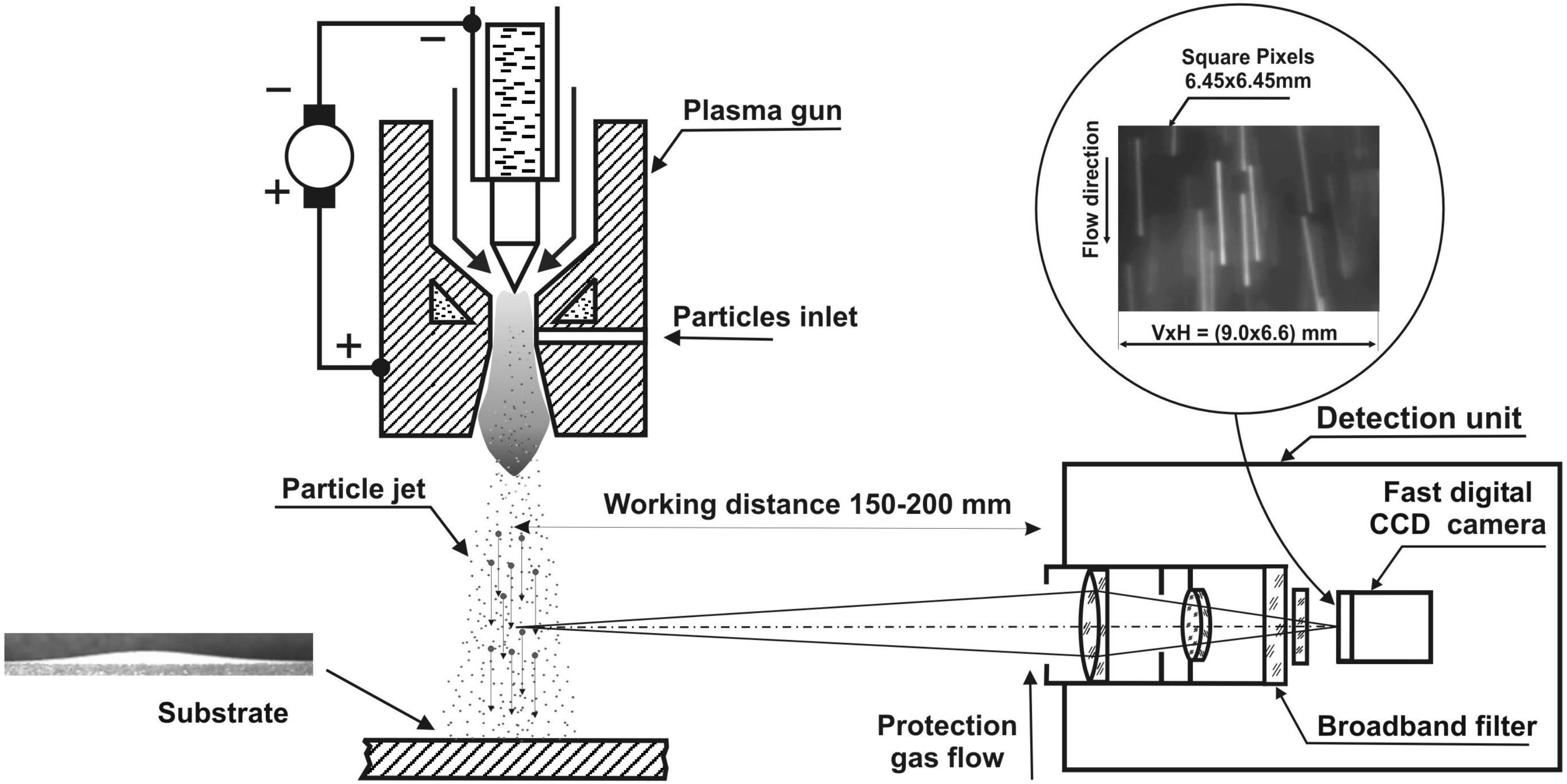

Plasma gun
Particles inlet
Particle jet
Working distance 150-200 mm
Substrate
Protection
gas flow
Square Pixels
6.45x6.45mm
Flow direction
VxH = (9.0x6.6) mm
Detection unit
Fast digital
CCD camera
Broadband filter

FIG. 2.

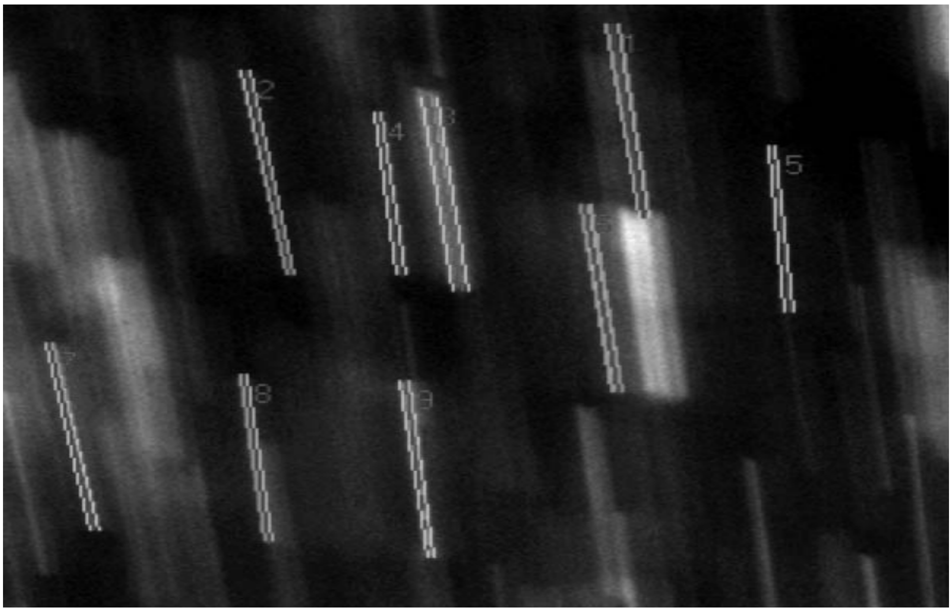
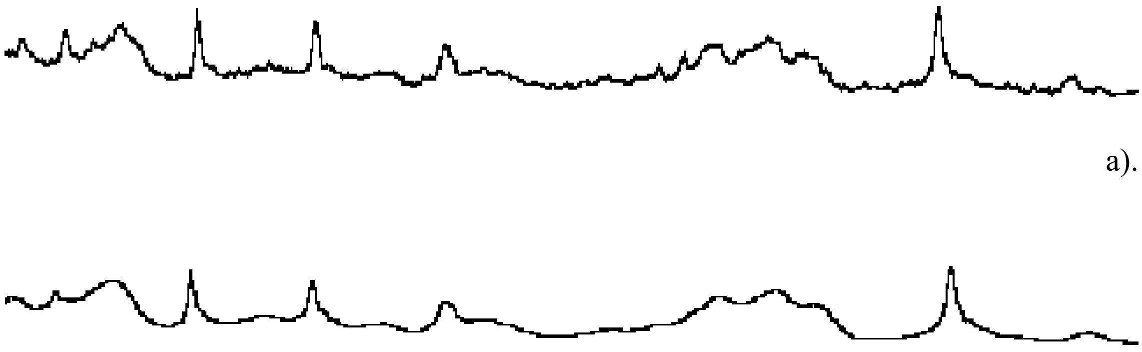


FIG. 3.



a).

b).

FIG. 4.

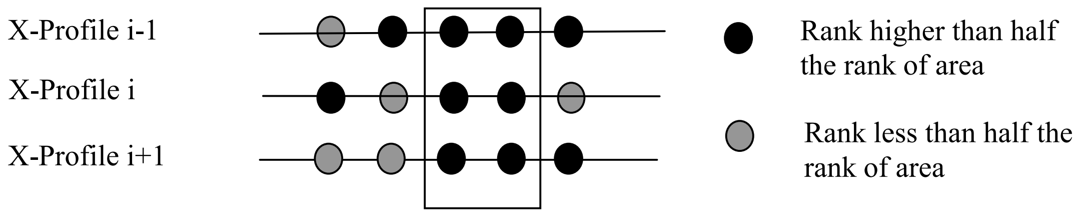

X-Profile i-1
X-Profile i
X-Profile i+1
Rank higher than half the rank of area
Rank less than half the rank of area

FIG. 5.

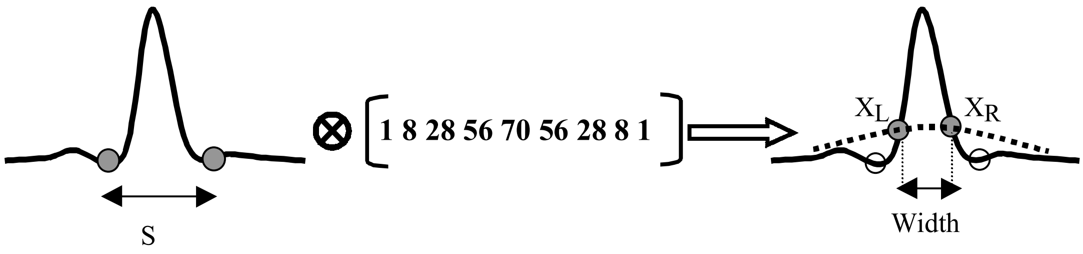


FIG. 6.

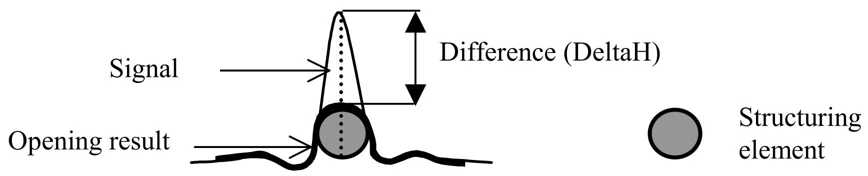

Signal
Opening result
Difference (DeltaH)
Structuring
element

FIG. 7.

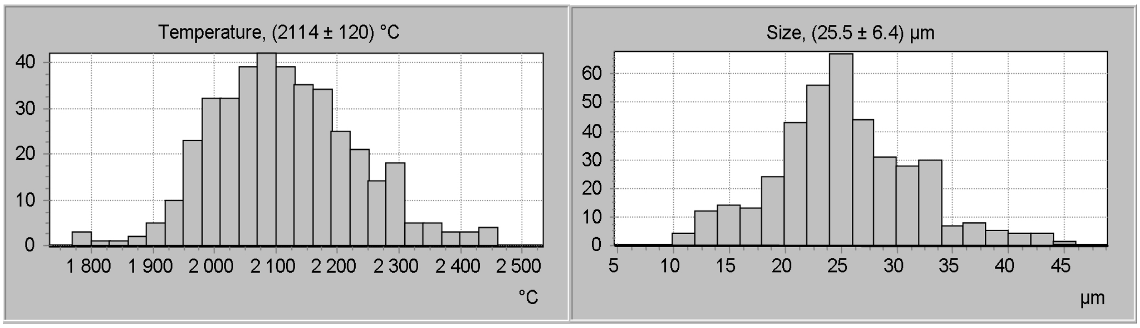

Temperature, (2114 ± 120) °C
40
30
20
10
0
1 800
1 900
2 000
2 100
2 200
2 300
2 400
2 500
°C
Size, (25.5 ± 6.4) µm
60
50
40
30
20
10
0
5
10
15
20
25
30
35
40
45
µm

FIG. 8.